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FINITE ELEMENT SIMULATION AND TESTING OF ISW CFRP ANCHORAGE

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ABSTRACT
Several Carbon Fibre Reinforced Polymers (CFRP) systems have been used successfully for strengthening of structures during the last decades. However, the fracture often occurs in the concrete adherent or in the adhesive interface when used for steel strengthening. As a consequence the CFRP is poorly utilized with a non ductile and brittle failure mode as the outcome. Mechanical anchorage can be used to utilize the full capacity of the CFRP materials but cannot yet challenge systems used for steel. Such systems can be used to transfer stresses from the CFRP material efficiently to the remaining structure. However, reaching the full capacity of the CFRP material is difficult since anchoring often courses premature failure modes such as crushing of the Fibre Reinforced Polymers (FRP), slip in the FRP and adjacent adherent, cutting of the fibres, bending of fibres and frontal overload. This paper presents a novel mechanical integrated sleeve wedge anchorage which seem very promising when perusing the scope of ultimate utilization of CFRP 8mm rods (with a tension capacity of approximately 140kN). Compression transverse to the CFRP is evaluated to prevent premature failure. The anchorage is modelled in the 3D finite Element program ABAQUS, just as digital image correlation (DIC) testing was performed to verify the finite element simulation. Also a new optimized design was produced to ensure that the finite element simulation and anchorage behaviour correlated well. It is seen that the simulation and DIC testing correspond well when strains on the barrel surface are compared. As a consequence it was possible to produce a new optimized anchorage which utilized the full capacity of the 8mm CFRP rod.

KEYWORDS

Anchorage, FRP, mechanical, testing, finite element

INTRODUCTION

Designing with FRP materials provides solutions, which are cost-efficient, easy and fast to install and at the same time durable (especially free of any corrosion risk). Such materials have been used for Repair, retrofitting or strengthening of the civil infrastructure during the last decades and gained acknowledgement for the various applications. Several strengthening FRP systems are available such as FRP rods (Mohamed *et al.*2008)
, (De Lorenzis *et al.* 2007), grid (Blanksvärd *et al*. 2009), (Frankl *et al*. 2011) plates (Täljsten 2001), (Smith & Teng 2001) and sheets (Yuan *et al.* 2003), (Giorgio & Marc'Antonio 2007), Also the systems have been used for pre- and post-tensioning. External post-tensioning of existing buildings amplify the shear and flexural capacity in the ultimate limit state and prevents large deflection and crack-openings in the service limit state which makes this technique very desirable. The existing external post-tensioning systems are typically an extension of already non pre-stressed systems where an anchorage device, specially tailored for the FRP geometry and property, is used. Examples of such systems are: a) FRP plates/strips, (Sika 2004) who uses mechanical anchorage; b) (Stöcklin & Meier 2001), (Czaderski & Motavalli, 2007) where the plate is applied with a gradually anchorage method (without mechanical anchorage) and c) sheets (Triantafillou, et al., 1991), (Wu, 2007). NSMR (Near Surface Mounted Reinforcement) has shown to be a very efficient strengthening method where the FRP bar is glued into a notch in the concrete surface (Nordin & Täljsten 2006), and (Wu 2007). The high tensile strength of FRP materials (especially Carbon) is however only utilized fully in FRP application if sufficient anchorage is provided. Figure 1a shows examples of a fracture when using NSMR CFRP rods for strengthening concrete structures (Intermediate crack de-bonding). Also when strengthening steel structures, often fracture in the adhesive bonding between the FRP and steel adherents is seen, Figure 1c. Forces are normally transferred through joints and connections which introduces high local stresses. As a consequence brittle and rapid fracture occurs with only little ductility. One of the main challenges of the FRP application seems to be desirable stress transfer in FRP anchorage/connections to the remaining structure. A desirable stress transfer in the anchorage zone is deemed to i) provide utilization of the FRP material, ii) ensure full use of the FRP ductility and iii) protect the anchored FRP against extreme environments. Mechanical anchorage of FRP is one of the methods

which are believed to provide such a mechanism. However these anchorages provide an active pressure transverse to the FRPs fibre direction which can introduce premature failure modes such as crushing of the FRP, slip in the FRP and adjacent adherent, cutting of the fibres, bending of fibres and frontal overload – Failures which prevents the FRP from being utilized, Figure 1b. Theoretical evaluation and measurement of the stress distribution can be very difficult since the mechanical anchorage is an advanced closed system.

a) b) c)

Figure 1. a) Failure of CFRP NSMR failure in concrete beam, b) Slippage in mechanical anchorage used for CFRP rods, c) Adhesive de-bonding between steel and CFRP laminate.

Numerical models built from axisymmetric elements have been used to give researchers an improved knowledge concerning the longitudinal pressure distribution onto a rod and also the ability to control and handle these stresses. The handling aims to optimize principal stresses along the anchorage and thus prevent premature failure. Two main techniques mainly used for this purpose are an angle difference or a curved interface between the outer wedge surface and the conically shaped inner surface of the barrel. Such systems allow higher compressive stresses on the rod at the unloaded end of the anchorage and less compression at the loaded anchorage end (the loaded anchorage end is where the CFRP rod is in tension) to be achieved, (Campbell *et al*. 2000), (Al-Mayah *et al.* 2007). Confinement (encircling the fibres) combined with transverse pressure is experienced to utilize the FRP material more. This paper presents a novel way of anchoring CFRP tendons using controlled compression in a confined environment. This technique is believed to solve some of the shortcomings related to mechanical anchorage of FRPs. The integrated sleeve wedge (ISW) anchorage system (Schmidt *et al.* 2010, 2011) is presently being researched and developed further at the Technical university of Denmark (DTU).

INTEGRATED SLEEVE WEDGE (ISW) ANCHORAGE METHOD

a) b)

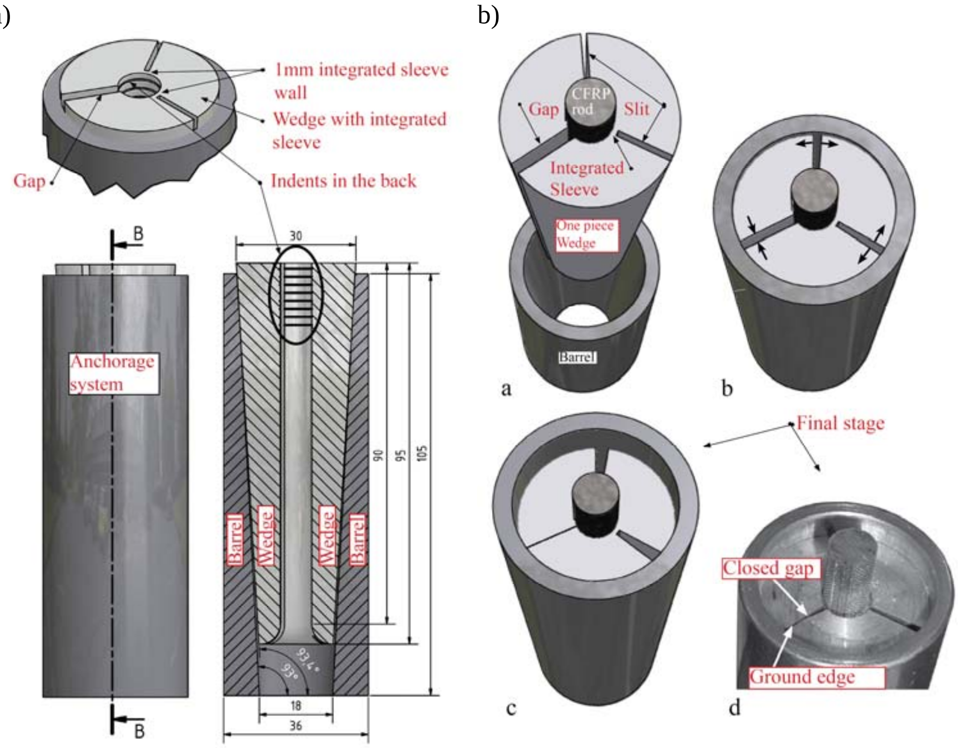


Figure 2. a) First original ISW anchorage b) Mounting of the (ISW) anchorage (Schmidt *et al.* 2011)

The integrated sleeve-wedge anchorage consists of two pieces: 1) The ISW and 2) the barrel. The anchorage is produced with an angle adjustment between the conically formed inner surface of the barrel and the outer surface of the wedge. The wedges are connected via an integrated sleeve Figure 2a. Figure 2b describes the installation procedure of the CFRP rod when anchoring by the integrated wedge-sleeve anchorage is performed. Also the subsequent pushing of the wedge into the barrel is shown (*installation or presetting procedure*). The ISW has three cuts along the longitudinal axis of a hollow wedge where two of the cuts are stopped 1 mm short of the inside hollow of the wedge (*slit*). The third cut is cut through to the inner hollow (*gap*). Installation is performed by opened the gap enough for the 8mm CFRP rod to be mounted, a). The wedge and enclosed rod are installed into the barrel where the slits open and the gap closes when presetting is performed b) and c). Circumferential gripping of the CFRP rod produces a confinement pressure. Consequently the fibre does not escape through the gap which finally closes (c and d). The gap size can be varied in order to control the pressure onto the rod.

FINITE ELEMENT MODELING AND DIC TESTING

ABAQUS was used to simulate and thus predict the anchorage behaviour, Figure 3a. Local coordinate systems to the barrel and rod were included in the construction of the finite element model. Using this method, evaluation of circumferential barrel strains was possible. Also it enabled anisotropic material properties to the CFRP rod to be included. Deformation applied to the ISW anchorage is shown in Figure 3a. Also the boundary conditions used in the finite element simulation is seen, where plane of symmetry is utilized at the gap location, Figure 3b.

Table 1. a) Interface properties and b) material properties

a)

Properties	Barrel-to wedge Interface	Wedge-to-CFRP interface
Behaviour	Tangential	Tangential
Surface	Isotopic	Isotopic
Contact mechanism	Penalty	Penalty
Surface to surface contact	Master/Slave	Master/Slave

b)

Anchorage comp	Material	*fy*,[MPa] mean/min	*fu*,[MPa] mean/min	*E* [GPa]
Rod	CFRP	--	2500/2200[ii]	165[iii]
Barrel	Steel	464/443[i]	512/494[i]	210[ii]
One-piece wedge	Aluminium EN-AW-6262-T9	358/355[i]	372/369[i]	70[ii]

i Tested values, ii Values provided by the manufacturer, iii Mean value from test

a) b) c) d)

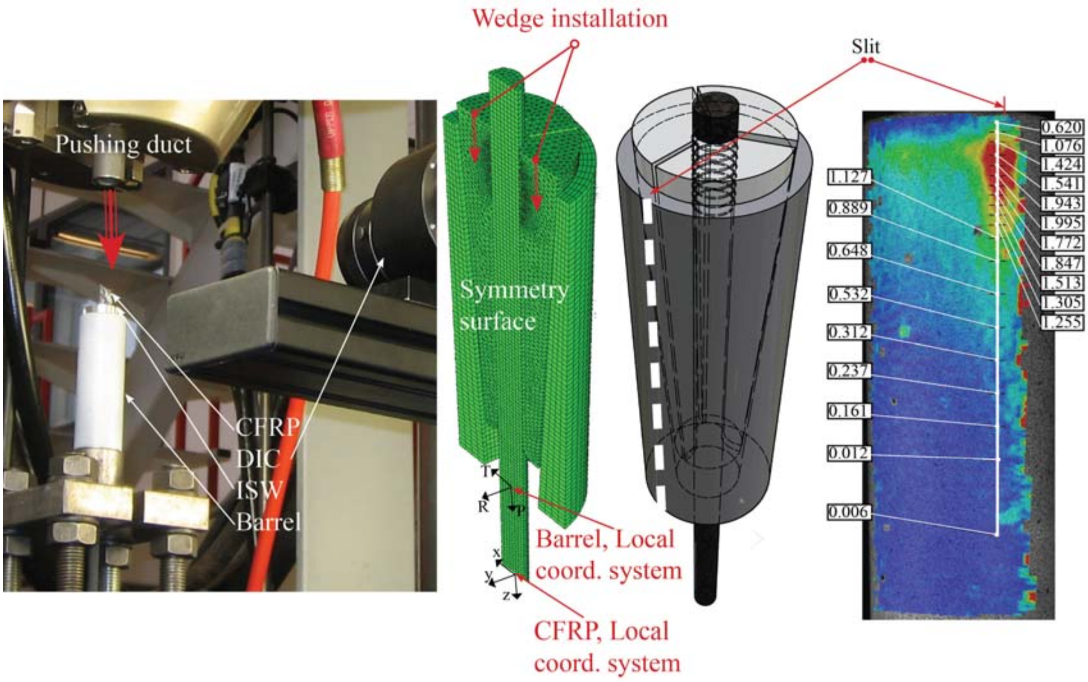


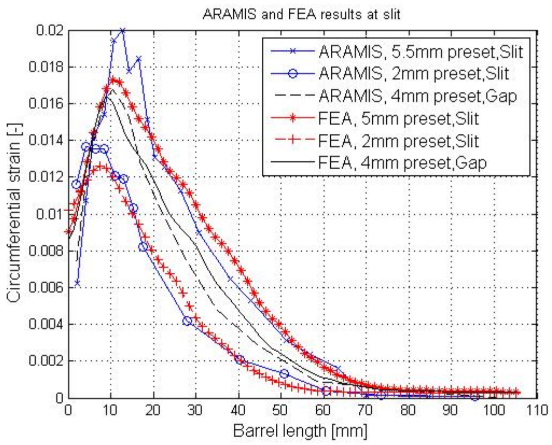
Figure 3. a) ISW Pushing duct, b) Finite element model used to simulate the ISW anchorage, c) and d) Example of DIC measurements conducted at the slits location

The ABAQUS time scale module was chosen as instantaneous and hardening isotropic when implementing the steel and aluminium materials. In addition, hexagonal element was used for the barrel and CFRP rod whereas a tetrahedral element was applied for the ISW which is more geometrically complex. Table 1a shows the two different interfaces properties used for the barrel-to-wedge and wedge-to-CFRP rod interfaces and the material properties was implemented in accordance with Table 1b (along with a plastic regime)

DIC testing
Also testing of the ISW anchorage was conducted using a pushing-presetting duct (Figure 1a) mounted in an INSTRON 8502 universal testing machine. The ISW was installed into the barrel using this duct which allowed a space for the CFRP rod to stick out of the unloaded anchorage end. 3D Digital image correlation (DIC) system (ARAMIS) optical measurement was used to measure surface strains of the barrel every 0.5 seconds while a 2 mm/min installation of the ISW was applied (pushing it into the barrel). In the full testing programme three locations was measured where the cameras were positioned at different locations. a) gap location, b) slit location and c) the location in between the gap and slit. These locations were deemed to be of most importance in the anchorage system since they reveal the anchorage barrel deformations which can be compared to the finite element simulation. Examples of the measurement performed at the gap and slit locations are shown in Figure 4a.

VALIDATING THE FINITE ELEMENT MODEL USING DIC EQUIPMENT
Figure 4a shows the comparison between representative numerical results and DIC measurements at the slit and gap location when the installation was performed. In general a peak value of strain at the unloaded anchorage end is observed to be higher in the test results at a penetration of 2mm and 5.5 mm (slit) and 4mm (gap) than that obtained in the numerical simulation. The larger peak strain value is dedicated to inherent variation in testing as well as the actual measured values from the DIC system.

¨a) b)



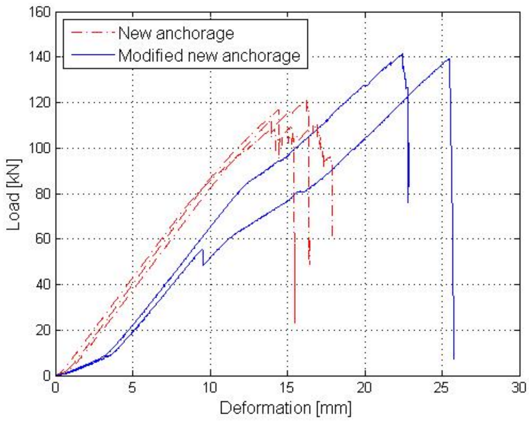


Figure 4. a) Example of measured and simulated circumferential strains at the slit and gap location. b) Tension capacity of new modified anchorage.

The curves reveal high circumferential strains at the unloaded anchorage end and thus a pressure which seems to be transferred to this area through the differential angle between the integrated sleeve wedge and barrel. This could indicate that higher compression stresses in the CFRP-to-ISW interface are developed in the unloaded end of the ISW anchorage. However, since the barrel wall is thinner in this area, the magnitude of compressive stress on the CFRP tendon is difficult to evaluate from the circumferential strains. Having a good correlation between the finite element simulation and the DIC measurements from the barrel surface enable a method to predict the compression stress transferred CFRP-to-ISW interface and thus a method to optimize these.

COMRESSION OF STRESS DEVELOPMENT AND TENSION CAPACITY
Conducting measurements on the outer surface of the barrel in combination with finite element modelling has indicated a good correlation. Consequently it is deemed that the finite element simulation can predict the compression stress in the CFRP-to-ISW interface. The predicted compression stress is depicted on Figure 5b. It is seen that the stresses are largest at the unloaded end of the anchorage and zero at the loaded end. This allows a more desirable distribution of the principal stresses since small compression stress is present where high tension stress is applied to the FRP material. The confinement seems to be of high importance since it allows a very high compression stress level. However, a way to be more confident in the good correlation between finite element simulation and testing is by producing a new optimized anchorage, Figure 6c. The new ISW anchorage has changed geometry which changes the stress transfer and thus the behaviour.

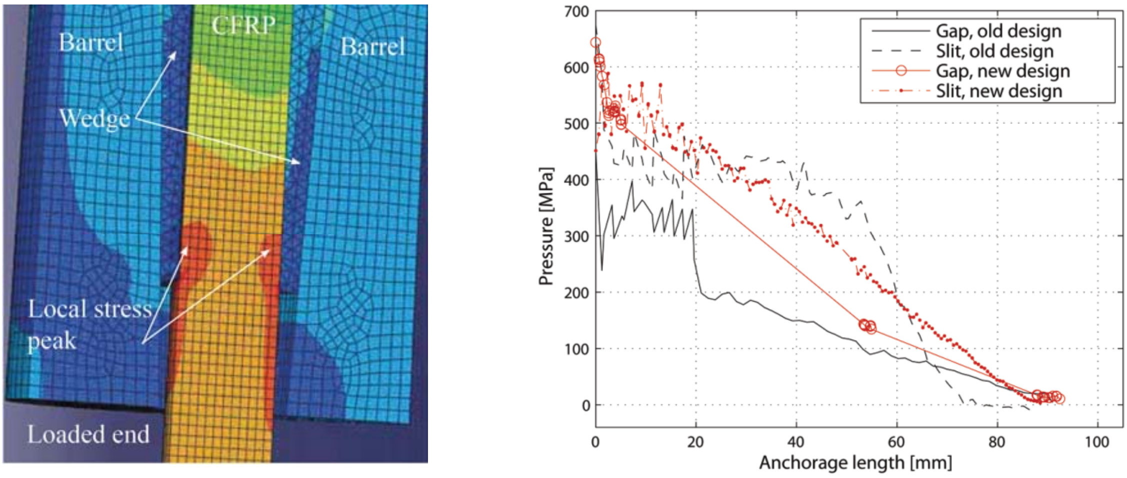


Figure 5. a) High local stress intensity peaks at the loaded anchorage end b) Compressive stress from old/original and new anchorage design along the FRP/ISW interface (0mm is the unloaded end)

TENSION CAPACITY OF ANCHORAGE

Figure 6a and 6b shows examples of testing performed using the new anchorage design. Viewing the pictures it seems that a desired fracture (full utilization of the rod) is reached for both cases. However, the Figure 6a represents a test where a tension capacity of 139kN is reached whereas Figure 6b shows fracture at a load of 113kN. This premature fracture was due to high local stress peaks at the loaded anchorage end, Figure 5a. These peaks were initially deemed to have no influence on the ISW anchorage capacity. However, realising a capacity of 113,117 and 121kN it was decided to make a very small differential angle change (approximately 0.1^{o}) which reduces the stress peaks at the loaded end. As a consequence the capacity was increased to 139 and 141kN.

a) b) c)

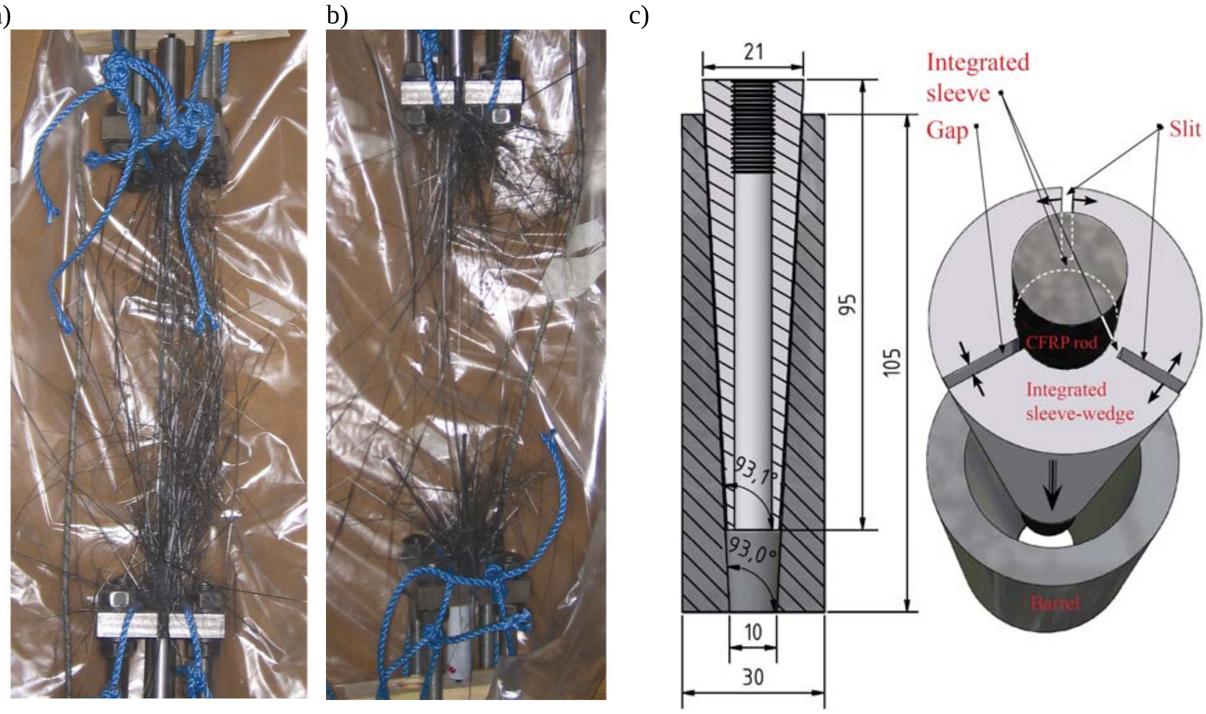


Figure 6. a), b) CFRP tension fracture using new ISW anchorage. c) New ISW anchorage

Table 2, shows the results from the old/original- and new ISW anchorage and verifies more thoroughly the finite element results. Having a manufacturer declared mean tensile CFRP capacity of 120kN the obtained anchorage capacities are considered sufficient. Tension testing of the old/original design was performed using a force controlled Instron 8502 universal tension machine, with a tensile capacity of 250 kN whereas tensioning of the new design was conducted with a deformation rate of 2mm/min.

Table 2. Results from original and new ISW anchorage testing

	Test results [kN]				
	1	2	3	4	5
Original ISW anchorage (Figure 2a)	148	142	144	146	146
New ISW anchorage (Figure 6c)	121	117	113	139	141

CONCLUSION

No efficient competitive post-tensioning systems for CFRP tendons have yet been developed, though research has been ongoing for the past decades. A great challenge lies within anchorage of the FRP tendon itself, resulting in several attempts to develop mechanical anchorage systems. Capacity of such anchorages is inconsistent, and from the experimental results seen in the literature, only small differences in the mounting procedure greatly affect performance of the anchorage. Hence the difference between a successful anchorage and an unsuccessful anchorage is small. Using the ISW system seems to prevent premature failure and ensure control of the stress transfer between CFRP and ISW. A plane-symmetric three-dimensional finite element model of the ISW anchorage was built, in which the barrel-to-wedge and wedge-to-CFRP rod interfaces have been considered. The simulated barrel surface strains were found to correlate well with the DIC measured barrel surface strains, this giving confidence in the modelling technique. Also this confidence was amplified when a new optimized design was produced which reached the same tension capacity as the original design. All tests failed within approximately 100 to 125% range of the mean ultimate capacity of the rods specified by the manufacturer. A good correlation between tests and theory was found and the model itself was seen to describe the correct behaviour and tendency when pressure was applied to the interface

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